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A simulation modelling study of water pollution caused by outwintering of cows.

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A simulation modelling study has been carried out of water pollution due to outwintering of beef and dairy cows on sacrifice field areas. Use has been made of the weather-driven MACRO model to simulate rapid transport of components of deposited excreta to field drains through macropores in saturated soil during or after rainfall. Such saturated soil conditions arise around the periphery of field areas which have become poached due to trampling by animal hooves. Simulations were set up to represent outwintering experiments carried out over two winters at two sites. Further simulations were set up as scenario tests over 10 years' weather at the same two sites. Simulated results show that outwintering is likely to lead to significant levels of water body pollution by ammonium and phosphorus. Results also show no benefit in periodically moving a feeder to a different location in the grassland field, as simulated pollution levels appeared to be similar for a moved feeder to those for a static feeder. The study demonstrates the value of a hydrological model previously calibrated and tested at sites with continuous measurements of outflows, which can be exploited in scenario tests for a field situation which differs slightly from that at the calibration sites.

Keywords
Outwintering cows; Hydrological model; Weather; Pollution; Phosphorus; Ammonium

Highlights

- A previously calibrated hydrological model has been exploited in scenario tests.
- Macropore flow in saturated soil exacerbates contaminant transport to field drains.
- Poaching by animal hooves leads to a saturated soil zone around the poached area.
- Outwintering causes water pollution by ammonium and phosphorus via field drains.
- Outwintering of cows should be discouraged on environmental grounds.

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1. Introduction

Weather-driven simulation models, which link contaminant transport processes with soil hydrology, have been found to be particularly valuable for the study of diffuse pollution of water bodies arising from agricultural activities. The Swedish MACRO model has been developed to simulate the hydrology of a soil with field drains and with a two-domain representation of the soil pore-space, together with processes by which contaminants are transported through the soil to the drains (Jarvis, 1994, Jarvis et al., 1999). This model has previously been calibrated and tested, using data from soil conductivity measurements, and from field sites instrumented to measure discharges via field drains of contaminants such as phosphorus, ammonium and E.coli micoorganisms (McGechan et al., 2002; McGechan, 2002; 2003a). These calibration simulations demonstrated the value of considering macropores as a domain of pore space separate from the soil matrix, for simulating transport of particulate contaminants such as inorganic phosphorus sorbed onto mobile faecal particles. The calibration measurements were very demanding in resources, but there are further opportunities for exploiting the model in scenario tests using long periods of weather data and for a field situation which differs slightly from that at the calibration sites. This study describes such scenario tests representing outwintering of beef and dairy cows in 'sacrifice fields', a practice which is becoming more common as a low cost alternative to providing and maintaining winter housing for livestock, but which is causing concerns about environmental pollution implications. This required some adaptations to the normal procedures where a uniform field is represented in MACRO simulations, to represent a field with a small area of severely damaged soil where animals congregate in wet winter conditions. The adapted modelling procedure, together with the previous calibrations of MACRO for a uniform field, have been used to estimate the extent of ammonium and inorganic phosphorus losses to water bodies via field drains during the winter period from a field with cows being fed silage in a feeder ring.

2. Background and modelling tools

2.1. Description of problem

Livestock systems pose a risk of water pollution by contaminants such as nitrates, ammonium, phosphorus and pathogens (Hooda et al., 2000). In general, grazing livestock tend to spend a proportion of their time congregating in certain areas of a field such as around gates, feeders, drinking troughs or where there is shelter from wind or rain. However, in the outwintering situation, there is a particularly marked uneven spatial distribution, with cows spending a very large proportion of their time in the vicinity of feeders, since with little grass growth there is no incentive to roam over the field to find fresh standing grass to eat. Trampling by hooves in a concentrated area leads to compaction and soil damage ('poaching'), particularly when the soil is wet. Rainwater cannot infiltrate through the compacted soil surface so puddles form in hoofprints. Also, a high proportion of the daily excretion of urine and faeces is deposited in the poached area. Hence the concentration of excreted pollutants rises to a high level in hoofprints, other puddles and ponding water. The only route by which water can move is by surface runoff to a less compacted strip at the periphery of the poached area, where the heavily contaminated water can infiltrate the soil surface. During rainfall, rapid overland flow occurs to this peripheral strip, leading to saturated soil conditions down to the level of the water table and the field drains.

In comparison with the outwintering situation where excretion takes place directly onto the soil surface at a time and under conditions conducive to high losses by leaching to the drainage system, if livestock are housed during winter manure or slurry are collected for subsequent field spreading. Such spreading should be carried out in a controlled manner, at a time of year when plants are growing rapidly so can use the nutrients they contain as a valuable asset to substitute for bought-in mineral fertilizer, potentially minimising the level of environmental pollution of waterbodies. Vinten et al. (2004) measured higher levels of contamination of field drain discharge water by E.coli pathogens from grazing animals depositing faeces directly onto fields, compared to that from slurry applications.

In contrast to the UK, it is normal practice in New Zealand for dairy cows to spend the winter period outdoors in ‘winter runoff units’, and there are major concerns about contamination of water bodies during winter from such units (Monaghan et al., 2007).

2.2. Through-soil transport in saturated soil

Some simple soil hydrological models describe water movements only in the vertical direction, from rainfall infiltrating the soil surface, to the level where it is taken up by plant roots, or by deep percolation down to groundwater. However, in northern Europe, many agricultural fields have field drains requiring a more complex representation of the hydrology with water movements in both horizontal and vertical directions. Also, for some purposes it is beneficial to split the modelled soil pore space into two ‘domains’, the small soil matrix pores within soil aggregates, and the ‘macropore’ domain of worm-holes and spaces around soil aggregates. Of particular interest is the process of ‘macropore flow’ or ‘by-pass flow’ in saturated soil where contaminants pass rapidly by the easy path around soil aggregates to field drains at a very short interval following deposition. During the winter period, this form of transport occurs when the soil water content is at or near saturation, usually with a water table rising to near the soil surface. Ponding and surface runoff are often observed in such conditions. Ammonium derived from excreted urine passes rapidly to field drains by macropore flow, but if it enters the soil matrix within aggregates it becomes sorbed and eventually converted to nitrate by nitrification. Similarly, ’particulate phosphorus’, which is essentially inorganic phosphorus sorbed onto mobile faecal particles, passes rapidly by macropore flow but is trapped if it enters the soil matrix.

2.3. *Basic features of MACRO model*

The main features of the MACRO model, including the hydrological and contaminant transport equations in two ‘domains’, have been described in detail by Jarvis (1994). The hydrological routines in MACRO are similar to many other soil water models, with the tension (water release) and hydraulic conductivity relationships for specified layers in the soil profile represented by mathematical functions, enabling Richards’ (1931) equation to be solved at successive timesteps. MACRO differs from other models in its treatment of processes in the larger soil pores (macropores) when capillary forces are very low, so water movements can be assumed to be driven by gravitational forces alone. The boundary between the macropore and soil matrix (micropore) domains is considered to occur at a soil water tension of 1.2 kPa (the 'break point'), with the corresponding water content and hydraulic conductivity values given by mathematical functions. In the soil matrix pore region where both capillary and gravitational forces must be considered, the hydraulic functions are as described by Brooks and Corey (1964) and Mualem (1976). The break point tension represents soil which is actively draining so it is considerably wetter than field capacity (which is commonly considered in the UK to occur at a tension of around 5-6 kPa). In MACRO, contaminant transport is treated separately with different concentrations in each of the two domains. Account can be taken of degradation of the contaminant, and also sorption of the contaminant onto soil components. A special version of MACRO to simulate colloid-facilitated transport of contaminants has also been developed (Jarvis et al., 1999). This version requires two sequential simulations: the first represents transport of the colloid taking account of trapping or other constraints to colloid movement; the second simulation represents transport of the contaminant taking account of sorption both onto colloids and onto static soil components. All simulations with MACRO require records of historic precipitation and other weather variables required to estimate evapotranspiration. While the normal interval for such variables is one day, the hydrological routines in MACRO benefit from the option of using hourly records of precipitation.

2.4. *Previous studies using the MACRO model*

Selection of parameter values representing the water release and hydraulic conductivity curves for calibration of the MACRO model was based on a similar calibration of another Swedish model SOIL (Jansson, 1991), as described by McGechan et al. (1997). For this earlier calibration study, field and laboratory measurements had been made for three soil types from Scottish sites. Calibrated MACRO simulations with ammonium as the contaminant (McGechan, 2003a) were tested and found to give good fits to data measured following slurry spreading at an instrumented drained plot field site at Easter Howgate (near Edinburgh) by Parkes et al. (1997). Calibrated simulations with the special colloid version of MACRO and inorganic phosphorus as the contaminant (McGechan et al., 2002; McGechan, 2002) were similarly tested against drained plot field measurements following slurry spreading at a site near Dumfries (Hooda et al., 1999). The colloid version of MACRO was also tested against phosphorus loss data at the same Dumfries site during autumn grazing (McGechan, 2003b).

3. Information and data for modelling

3.1. Field sites

The outwintering project with which this modelling study is associated involved field observations at four sites in England, plus one in Wales and one in Scotland. Observations at the sites during two winters were records of cow numbers, dates of the beginning and end of the outwintering period in the sacrifice fields (Table 1), type and location of feeders, feedstuffs in the feeders, as well as assessments of the state of ground in different parts of the grazing fields. However, the procedure for putting silage bales into the feeders differed between the sites. At the Scottish site and two of the English sites, the feeder remained in one position near the edge of the field throughout the outwintering period, and a new bale of silage was added to it every few days. At the Welsh site and the other two English sites, wrapped bales were put out in various positions over the field area at the beginning of the period, then one bale was unwrapped every two or three days during the outwintering period. Whenever a new bale was unwrapped, a feeding ring was placed over the top, having been moved from the previous unwrapped bale position. The most detailed and useful information was obtained from at the Scottish and Welsh sites, representing the two options regarding a static or moving feeder. In addition at the Scottish and Welsh sites, some measurements of contaminant concentrations and streamflow rates were made on a few occasions (mainly before the start of and after the end of the outwintering period) in streams below the grazing fields. Observations at the English sites concerned outwintering procedures and practices in general terms (with no measured data), as a background for a series of farmers' workshops (Barnes et al., 2013).

3.2. Observations at the Scottish field site

Periodic visits were made to the Scottish field site (at Easter Howgate, near Edinburgh) over the outwintering periods in both winters, when qualitative observations were made about the state of the ground, and photographs were taken. Within a very short period after the start of outwintering in the first winter, a circular area immediately surrounding the feeder had become seriously compacted ('poached') with no sign of growing grass and puddles forming in deep hoofprints. Surrounding this seriously compacted area was a peripheral zone with patches of seriously compacted ground including water-filled hoofprints and some patches of deposited faeces, but with an area with standing grass and little damage between the patches. While the areal density of the patches in this area reduced with increasing distance from the feeder, it was estimated that on average the patches covered 50% of the peripheral area. Beyond the peripheral area the remainder of the field appeared to have standing grass and little compaction damage to the soil. The radius of the outer boundary of the seriously compacted area was estimated at 5m, and of the outer boundary of the peripheral zone at 30m. The feeder diameter was approximately 2m. Observations, supported by photographs, about the locations of the cows indicated that their time was divided roughly half-and-half between the damaged area near the feeder and the undamaged parts of the field away from the feeder. The areal density of excreted urine and faeces deposited in each area of the field would reflect the proportion of time spent by animals in each area

3.3. Detailed assessment of poaching at Welsh field site

A procedure for assessing the extent of poaching in different parts of a field after outwintering has been described by Barnes et al. (2015). The procedure was applied at all six sites in the project, but was most relevant where the feeder was moved to different locations over the winter such as at the Welsh site (at Trawsgoed, near Aberystwyth). At this site, the field had been divided into two, with a 'sacrifice area' with outwintered dry dairy cows, and a control area with no cows. The bales had been placed in the sacrifice area in one or two rows 20-40m from one side of the field. After the winter grazing period, in the grazed (sacrifice) and control parts of the field, visual assessments supported by photographs were made during site visits using a grid with 40 x 40 m divisions of the area, to give an average degree of poaching in each grid square. In practice, the most useful information for the simulation study was the size of a small circle with a radius of about 5m with over 80% poaching around each feeder position.

3.4. Weather data

Recorded daily meteorological variables were obtained for precipitation, temperature, radiation and windspeed at Trawsgoed and Easter Howgate, near to the Welsh and Scottish experimental sites. In addition, hourly precipitation had been recorded for another location near Easter Howgate. A disaggregation procedure associated with the MACRO model was used to generate synthetic hourly precipitation data from the daily records at Trawsgoed.

4. Modelling procedure

4.1. Deposition of contaminants by excretion

Assumptions about quantities and concentrations of liquid, nitrogen and phosphorus deposited by excretion for a single cow were based on various literature values. Values for slurry as presented in RB209 (2010) are listed in Table 2. Derived daily quantities and concentrations are listed in Table 3, assuming that the total volume of slurry is made up of a 78% contribution from urine plus 22% from faeces, as assumed for dairy cows by Lantinga et al,.(1987). Very similar values for slurry have also been presented by Dyson (1992). For the current modelling study, the quantities and composition of inorganic phosphorus deposited shown in Table 3 were assumed, with the adjustment of 62/142 as the model works with P rather than P_2O_5 vales.. However, a higher value of 5.1 g/l than that listed in Table 3 was assumed for the N concentration in deposited urine. This was the same as previously assumed for the concentration in urine excreted by dairy cows by McGechan and Topp (2004), based on figures presented by Jarvis (1993), and assuming a volatilisation loss of 8.6% between excretion and infiltration to the soil based on Hutchings et al. (1996). The justification for this higher concentration figure is that concentrations of around 3.3 g /l in Table 3 are for slurry where losses by volatilization are likely to be much higher than where urine is excreted directly onto and into the ground. Also, since the concentrations shown in Table 3 are almost the same for all cow types, it seemed reasonable to assume that the concentration for a grazed dairy cow would also be applicable for beef cows. Some more recent measurements of N concentrations in urine as excreted from lactating dairy cows are 6.6 and 4.5 g/l at different dates in summer from Burchill et al., 2017, and 8.3 g/l in autumn and 5.3 g/l in spring from Forrestal et al., 2017. These figures suggest that the N content of urine is very variable, but the assumed figure of 5.1 g/l is a reasonable, typical value. It was also necessary to make an assumption about the concentration of colloids onto which inorganic phosphorus is sorbed when excreted; this was taken to be 20 times the inorganic phosphorus concentration, based on previous calibrations of the MACRO model for phosphorus (McGechan et al., 2002). The quantities of urine and faeces deposited are calculated from the figures per cow in Table 3, taking account of the localized stocking rate in various parts of the field.

4.2. Hydrology of field sites

Hydrological parameters for two soils (Table 4) are based on measurements from which the MACRO model had previously been calibrated. For the sandy loam soil at the Scottish site were based on those for a nearby site with the same soil type. For the silty clay loam soil at the Welsh site, these were based on those for a site with a similar soil type at the Crichton Royal Farm near Dumfries (McGechan et al., 2002).

4.3. Subdivision of fields into zones for a static feeder

For a situation with a static feeder, such as at the Scottish experimental site, the approach was to subdivide the field into three areas (designated as Zones 1, 2 and 3), with separate simulations for each (Fig. 1). However, it was necessary to simplify the subdivision of field areas from the situation observed in the field (as described in Section 3.2), by considering the small patches of damaged ground further away from the feeder to be added to the central completely damaged area, and described as ‘Zone 1’. Since the ground in Zone 1 is completely compacted no water can enter the soil surface by infiltration. The only route by which water can leave Zone 1 is by surface runoff and the rate at which runoff takes place will be related to hourly rainfall. This leads to an immediately surrounding area (‘Zone 2’) where heavily contaminated water infiltrates at a rate dependent on the saturated infiltration rate of the soil profile (which is lower than the saturated conductivity of the surface layer of the soil). The area of Zone 2 will vary in proportion to the rate of runoff from Zone 1, dropping to zero in hours with no such runoff. Zone 2 is considered to be completely saturated, leading to macropore contaminant transport as described in Section 2.2. Zone 3 is the remaining area which is like a grazed field with a stocking density lower than the average for the whole field. The area of Zone 3 varies conversely with the area of Zone 2. From the estimated dimensions described in Section 3.2 for the static feeder, Zone 1 was calculated to be 7.5% of the field area, and the cows would spend 50% of their time in this area. A similar approach but sub-dividing the field into only two areas has been taken in two previous projects both relating to summer grazing (McGechan and Topp, 2004, McGechan et al., 2008).

4.4. Simulations for Zone 1

For MACRO simulations, all measured conductivity values were reduced by a factor of 1000 to represent soil which is compacted by cows’ hooves so no infiltration occurs. MACRO simulations produced time series of hourly runoff values which were almost the same as the input rainfall, but reduced slightly by evaporation from the soil surface, from the plant canopy surface water and by evapotranspiration, all of which have low values during the winter period. Since surface water and contaminants collect in puddles due to hoof indentations which restrict runoff, a separate simple runoff model with hourly MACRO output variables as inputs was set up in an Excel spreadsheet. In this, representation of the puddles was simplified by assuming a uniform surface pool with a 'target' depth of 10 mm. Evaporation during dry periods reduces the depth of the pool, while rainfall and excretion raise the depth with runoff occurring whenever the depth exceeds 10 mm. An exponential form was assumed for the dynamic equation representing runoff from Zone 1, with the rate of runoff proportional to the depth in excess of 10mm. The same form of dynamic equation for runoff from a surface pool (but with no 'puddles') has been assumed in hydrological models such as MACRO and SOIL (Jansson, 1991). A rate coefficient of 0.2 /h was assumed for this equation, again similar to that in the MACRO and SOIL models. Concentrations of ammonium, colloids and phosphorus in the surface pool and in the runoff water leaving the pool are adjusted each hour, taking account of additions by excretion and substance removal in runoff. Excretion took account of the stocking rate in Zone 1 being higher than the average for the whole field (Table 1). A loss of ammonium by volatilization from the surface pool was also assumed. The rate coefficient for volatilization was set at 0.1 /h, based on the volatilization model of Hutchings et al. (1996).

4.5. Simulations for Zone 2

MACRO simulations were carried out for Zone 2 with a constant hourly infiltration rate, resulting from a constant hourly value of the 'rainfall' input driving variable. The size of Zone 2 was varied in relation to the runoff from Zone 1 to give an infiltration rate which maintains saturated conditions but without runoff in Zone 2. By trial and error, 'rainfall' rates (representing the saturation infiltration rate of the particular soil profile) of 2.0 mm/h with the sandy loam soil or 1.8 mm/h with the silty clay loam soil were found to maintain these conditions. In hours with no runoff from Zone 1, the area of Zone 2 was set to zero. Use was made of the facility in MACRO to specify the contaminant concentration in rainfall to indicate the quantity of ammonium, phosphorus or colloids being applied in this zone. Daily average values of both the area of Zone 2 (Fig. 2) and the contaminant concentrations in 'rainfall' were calculated from the hourly values given by the Zone 1 spreadsheet runoff model.

4.6. Simulations for Zone 3

The procedure for MACRO simulations for Zone 3 was as it would have been if cows had been spatially distributed evenly throughout the field, but with a reduced stocking density. Again, use was made of the facility in MACRO to specify the contaminant concentration in rainfall to indicate the quantity of ammonium or phosphorus being applied in this zone.

4.7. Adaptation of simulation procedure for a moving feeder location

The three-zone representation in the simulation procedure was adapted to represent the situation where the feeder location changed periodically during the outwintering period. In the first instance, a hypothetical scenario was set up for the Scottish site assuming that the feeder would be moved twice, to give three equal-length sub-periods. This required that Zones 1 and 2 would be each divided into three sub-zones in the spreadsheet calculations, each Zone 1 sub-zone having an area 7.5% of the total field area. The second and third sub-zones during the first sub-period and the third sub-zone during the second sub-period would receive low levels of excreted contaminants similar to Zone 3, and have soil conditions as in Zone 3. During the second and third periods, after removal of the feeder from the first or second sub-zone, soil would be poached and contaminants remain in the surface pool represented by the runoff model; however, additions of new contaminants would be at a level similar to Zone 3 so the concentrations of contaminants in the surface pool would be declining.

The situation at the Welsh field site, with the feeder moved to a new location where a new bale was unwrapped every two or three days, was considered to be too complicated and too difficult to represent in simulations. However, a simplifying approximation to this situation was based on the above hypothetical situation for the Scottish site, with three feeder positions in three equal-length sub-periods. Analysis of the poaching records from the Welsh site with squares of approximately 40m side indicates high levels of poaching in each of three squares where the bales were located; poaching was at an intermediate level in squares adjacent to those with the bales and at a much lower level in squares well away from the bales. From the recorded percentage poaching in each square at the end of each of the two outwintering periods, the size of each of the three Zone 1 sub-zones was estimated to be 6% of the total field area.

4.8. Simulation sites, periods and scenarios representing outwintering experiments

MACRO simulations were carried out for winters 2009-10 and 2010-2011, for both the Welsh and Scottish sites with the numbers of cows and the periods in the fields as recorded at each site (Table 1). A fixed location feeder was assumed for the Scottish site, and a moving location feeder, approximated by the procedure described in Section 4.7, was assumed for the Welsh site. By way of a scenario test, further simulations were carried out for the hypothetical situations of a fixed location feeder at the Welsh site, and a feeder moved to three locations in three equal length sub-periods at the Scottish site. In every case, daily and cumulative contaminant flows through the field drains for the whole field were calculated by combining simulated results from each of the zones or subzones, weighted according to the area of the zone or sub-zone. In general, the largest contribution was found to come from Zone 2 or its sub-zones.

4.9. Scenario simulations over 10 years' weather

A further set of scenario simulations was carried out to investigate the effects of weather variability between winters. In every case, it was assumed that a group of beef cattle with assumptions about excretion would be identical to that in the winter 2009-10 at the Scottish (Easter Howgate) experimental site. Simulations were carried out in each case for 10 winters (2001-02 to 2010-11), two weather sites (Trawsgoed and Easter Howgate), two soil types (sandy loam and silty clay loam), and both for a static feeder and a moving feeder.

5. Results and discussion

5.1. Simulations for the field sites and experimental periods

Daily losses of both contaminants for the second winter at the Welsh site are shown in Fig. 3. This illustrates the event-driven nature of these losses, which rise to high levels during rainfall events but drop to zero during dry periods. For a comparison of effects of soil type, weather site and whether the feeder was moved, cumulative losses over each of the two winters are presented in Fig. 4.

In the main part of the field (Zone 3), losses of both ammonium and phosphorus were zero at the Scottish site during both winters, and very low at the Welsh site during the first winter; however, there were more significant losses of ammonium during the second winter at the Welsh site (Fig. 4). In this case, cumulative losses of ammonium over the outwintering period exceeded 17 kgN/ha, with the loss occurring mainly during a single event lasting about 5 days. Some surface runoff also occurred during this event

For the three-zone model with Zone 2 varying in area (Fig. 2), losses of both contaminants were always high from Zone 2, except during extended dry periods when the area of this zone dropped to zero. The overall loss from the whole field, calculated as a weighted mean by the procedure described in Section 4.8, was lower than in Zone 2 but still generally much higher than in Zone 3 (Fig. 4). The highest cumulative losses were around 37 kgN/ha for ammonium and around 3.4 kg/ha for inorganic phosphorus during the second winter at the Welsh site. Ammonium losses during the first winter at the Welsh site and during both winters at the Scottish site were somewhat lower, as were losses of phosphorus during the first winter at the Welsh site. Losses of phosphorus during both winters were substantially lower at the Scottish site compared to those at the Welsh site. However, differences in loss levels between sites must be partially accounted for because of the different animal types at each site with different assumed values for their excreta quantities and composition.

5.2. Testing alternative feeder position scenarios

Alternative scenarios of moving the feeder periodically during the winter at the Scottish site, and of a static feeder at the Welsh site, (as described in Section 4.7 and 4.8), were tested in simulations. At each site, and for both winters, the overall weighted mean losses of both contaminants were found to be slightly different with a moving feeder compared to a static feeder (Fig. 4). In each case slightly lower losses were found for the actual situation at each site, ie a fixed location feeder at the Scottish site and the moving feeder at the Welsh site. However, the differences are so low that it does not make a good economic case for the higher cost option of moving the feeder location.

5.3. Results of scenario simulations over 10 years' weather

Results of 10 year scenario simulations are listed in Table 5 as the average total loss of ammonium or phosphorus over each winter, together with the highest and lowest value in individual years, and the standard deviation. Variability between years was much higher for phosphorus with a standard deviation roughly half the mean value, than for ammonium with a standard deviation around one fifth of the mean. The effect of soil type, weather site and fixed or moving feeder was also greater with phosphorus than ammonium. Furthermore, for phosphorus with the hypothetical situations where soil type and weather site were reversed compared to the actual situation at the experimental sites, losses appeared to be significantly higher for the fixed compared to the moving feeder. However, the large differences for phosphorus in particular between sites where actual conditions at the experimental sites were considered were not born out in these scenario comparisons where the same animal type and length of outwintering period was assumed in every case. This indicates that the differences between animal types at the two sites must have had a much larger effect than those of soil type, weather or feeder location.

5.4. Comparison of results with those in previous diffuse pollution studies

In order to assess whether the pollution levels indicated by the simulated results should be of concern, it is interesting to make comparisons with pollution levels indicated by the previous studies in which the MACRO model had been calibrated and tested. (McGechan et al., 2002; McGechan, 2003b). In both these previous studies both simulated and measured polluting losses were presented following a number of single slurry spreading operation in winter. For ammonium, the highest loss was around 40 kgN/ha (McGechan, 2003b), and for phosphorus this was around 1.2 kg/ha (McGechan et al., 2002). In each case, the highest recorded loss was when slurry had been spread on wet ground at a location with high levels of rainfall during winter, a situation where best practice would indicate that slurry spreading operations should not be carried out. Simulated losses for an outwintering period are generally at a similar level to those for a slurry spreading operation, although the cumulative phosphorus loss for the second winter at the Welsh site (Fig.4) was around three times as high as that for the worst slurry spreading operation. Comparisons can also be made with measured losses of phosphorus in a number of studies as reviewed by Hooda et al., 2000. Hawkins and Scholefield (1996) measured an inorganic phosphorus loss of 0.2 kg/ha/year, from a fertilized permanent pasture with no slurry or manure applications and grazed by beef cattle; losses were low in this case since grazing took place during the summer with grass actively growing so animals would have been roaming over the whole field area. Hooda et al., 1999 measured inorganic phosphorus losses of 1.27-1.34 kg/ha/year, from fields cut for silage followed by grazing by sheep and dairy cows, and also receiving intensive cattle slurry inputs; these figures rose to 1.69-2.03 kg/ha/year where mineral phosphorus had been applied at 25 kg/ha in addition to manure or slurry. All these comparisons suggest that outwintering is a practice that should be discouraged on environmental grounds, in much the same way as slurry spreading in winter is discouraged.

5.5. Comparison of simulated with measured contaminant losses

Measured concentrations of ammonium and phosphorus in streams below the outwintering sites in Wales and Scotland were nearly all at a very low level. However, at the Scottish site there was some doubt about whether flows from the field drains did feed into the stream where the measurements were made. Also, it became apparent in retrospect that the timing of the measurements at both sites, in most cases before the beginning and after the end of the outwintering periods, was quite inappropriate. Only during the second winter at the Welsh site were any measurements made during the outwintering period, but even then the measurements were made on only five occasions each during dry weather. In a previous study comparing MACRO simulations of field drain ammonium concentrations with measured concentrations in a stream, the river 'reach lengths' had been measured and defined in a catchment model (McGechan, et al., 2008). Since there was no adequate description of the river system in the catchment at the Welsh site, a simpler approach was adopted by comparing ammonium loads in kg/day taking account of the flow rates in the stream and of the area of the field (Fig.5). These measured loads were quite close to the simulated loads on each of the five dates, which were all at low levels due to the dry weather (Fig. 5b). This comparison can be regarded as a validation of the model predictions only for periods when losses are likely to be low. The justification for the predictions of high losses during wet weather periods can only be from previous studies with the MACRO model where predicted losses were tested against continuous measurements at fully instrumented experimental sites. Results here suggest that occasional contaminant concentration measurements in a stream which catches an uncertain mixture of outflow from various fields have very little value, particularly if carried out only during dry weather when contaminant losses are likely to be low.

5.6. Implication of results for particulate contaminants in general

In a previous study (McGechan and Vinten, 2003), the special colloid transport version of MACRO, as used in the current study to describe transport of particulate inorganic phosphorus, was used to describe transport of E.coli microorganisms. In this previous study, simulated losses of Ecoli via field drains following slurry spreading in winter were found to be good fits to losses measured at a fully instrumented field site. Since both microorganisms and inorganic phosphorus are particulate contaminants excreted in livestock faeces, this implies that outwintering is likely to lead to water discharged to water bodies via field drains being contaminated by microorganisms including E.coli.

6. Conclusions

In this study, a model of contaminant transport previously applied to spatially uniform field with field drains (tile drains) has been adapted to a situation where there are large variations in both inputs and surface conductivities in different zones of the field. It is an example of an opportunity for exploiting a model in scenario tests using long periods of weather data and for a field situation which differs slightly from that at the calibration sites. It demonstrates the value of a hydrological and contaminant transport model which has been calibrated and tested at sites with instrumentation to continually measure outflows from field drains and contaminant concentrations in the outflows. Although such measurements are very demanding in resources, they are of much greater value than occasional contaminant concentration measurements in a stream below a field.

This study suggests that outwintering of beef and dairy cows on fields with field drains will lead to significant levels of water body pollution by ammonium and phosphorus, and probably also by other particulate contaminants including microorganisms such as E.coli. Such pollution arises due to rapid transport of components of deposited excreta to field drains through macropores in saturated soil during or after rainfall. Saturated soil conditions arise around the periphery of any field areas which have become compacted due to trampling (‘poached’) by animal hooves; this situation is almost inevitable during outwintering as animals spend most of the time in the vicinity of a feeder since with little growth in the grazed crop there is no incentive to roam around the field. Soil compaction due to trampling leads to a significant base level of pollution which is unavoidable. There is little or no benefit in moving a feeder to different locations periodically over the winter, as simulated pollution levels appeared to be very similar with a moving feeder compared to a static feeder.

The overall conclusion is that outwintering of cows is a practice that should be discouraged on environmental grounds.

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Table 1
Animal types and outwintering periods at two field sites

Site	Area	Animals		Animals enter	Animals removed
	(ha)	Type	Number	field	from field
Nr Aberystwyth, Wales	2.0	Dry dairy cows	10	30/11/2009	10/01/2010
	2.0		10	14/01/2010	24/01/2010
	2.0		10*	16/11/2010	28/02/2011
Nr Edinburgh, Scotland	1.8	Beef cattle	12	24/11/2009	15/02/2010
	1.8		12	24/11/2010	16/02/2011

*One cow removed on 09/02/2011 leaving 9 cows in field for remaining period

Table 2

Annual quantities per cow and nutrient concentrations in slurry as presented in RB209 (2010)

Type of livestock	% of year	Quantity (kg) (undiluted)	Nitrogen (N) (kg)	Phosphate (P_2O_5) (kg)
Dairy cows (6-9000 litres)	60	11.6	60	26
Beef cattle (13-25 months)	50	4.7	25	8

Table 3
Derived slurry nutrient concentrations and annual quantities per cow based on RB209 (2010)

Type of livestock	Housing period, days	Volume (m^3)			Nutrients (kg)		Concentrations (g/l)		
		Slurry	Urine	Faeces	Nitrogen N	P_2O_5	Available N	Inorganic P	Colloids
Dairy cows (6000-9000 litres) annual milk output	219	0.053	0.041	0.012	0.274	0.119	3.33	0.481	9.6
Beef cattle (aged 13-25 months)	183	0.0258	0.02	0.006	0.137	0.043	3.42	0.361	7.2

Table 4
Physical and hydraulic parameters of soils

Location	*Crichton farm, Dumfries*			*Easter Howgate, near Edinburgh*				
Soil	*Silty clay loam*			*Sandy loam*				
Layers	*Topsoil*		*Subsoil*	*Topsoil*		*Subsoil*		
	Surface	*Lower*		*Surface*	*Lower*	*Upper*	*Middle*	*Lower*
Layer depth (m)	0-0.1	0.1-0.3	0.3-1.0	0-0.1	0.1-0.3	0.3-0.65	0.65-1.0	1.0-1.5
Porosity (%)	52.6	49.9	46.2	54.6	52.4	55.6	35.8	29.8
Dry bulk density (kg/m^3)	1.26	1.33	1.43	1.21	1.33	1.32	1.70	1.86
Pore size distribution index	0.026	0.023	0.035	0.160	0.125	0.110	0.110	0.170
Residual water content (%) volumetric basis	4.0	4.0	4.0	7.5	7.5	7.5	7.5	7.5
Macroporosity (%)	2.35	3.01	1.08	12.5	8.3	8.7	3.9	4.9
'Break point' tension, (cm H_20)	12.11	12.02	11.96	12.10	11.90	11.90	11.90	11.90
Saturated hydraulic conductivity (mm/h)	375	208	166.7	1250	83.3	41.7	1.25	0.15
Hydraulic conductivity at break point (mm/h)	1.746	0.84	0.175	1.08	2.85	0.82	0.053	0.0071
Drain spacing (m)			7.0				7.0	
Drain depth (m)			0.65				0.65	

Table 5
Mean, maximum annual value, minimum annual value and standard deviation of cumulative annual losses of ammonium and phosphorus (kg/ha), from 10 year scenario simulations with different weather sites, soil types and for a fixed location or moving feeder. Urine and faeces deposition for beef cows as at the Scottish site in each case.

a. Ammonium

	Bu N3 FX	Bu N3 MF	Bu Cr FX	Bu Cr MF	Tr N3 FX	Tr N3 MF	Tr Cr FX	Tr Cr MF
Mean	25.7	29.8	23.3	27.1	26.3	30.2	23.3	27.0
Max.	34.6	36.6	30.1	32.1	32.7	37.9	27.9	32.7
Min.	17.6	20.4	16.8	19.7	20.7	25.4	19.0	23.5
St. Dev.	5.26	5.14	4.35	4.02	4.56	4.58	3.34	3.20

b. Phosphorus

	Bu N3 FX	Bu N3 MF	Bu Cr FX	Bu Cr MF	Tr N3 FX	Tr N3 MF	Tr Cr FX	Tr Cr MF
Mean	0.328	0.386	0.622	0.432	0.846	0.351	0.591	0.413
Max.	0.548	0.651	1.119	0.781	1.157	0.609	0.891	0.627
Min.	0.171	0.178	0.348	0.265	0.484	0.190	0.300	0.219
St. Dev.	0.130	0.157	0.256	0.179	0.274	0.106	0.222	0.146

Key to columns:
Weather: Bu – Easter Howgate, near Edinburgh; Tr – Trawsgoed near Aberystwyth
Soil type: N3 – sandy loam; Cr – silty clay loam
Feeder: FX – fixed location; MF – moving feeder

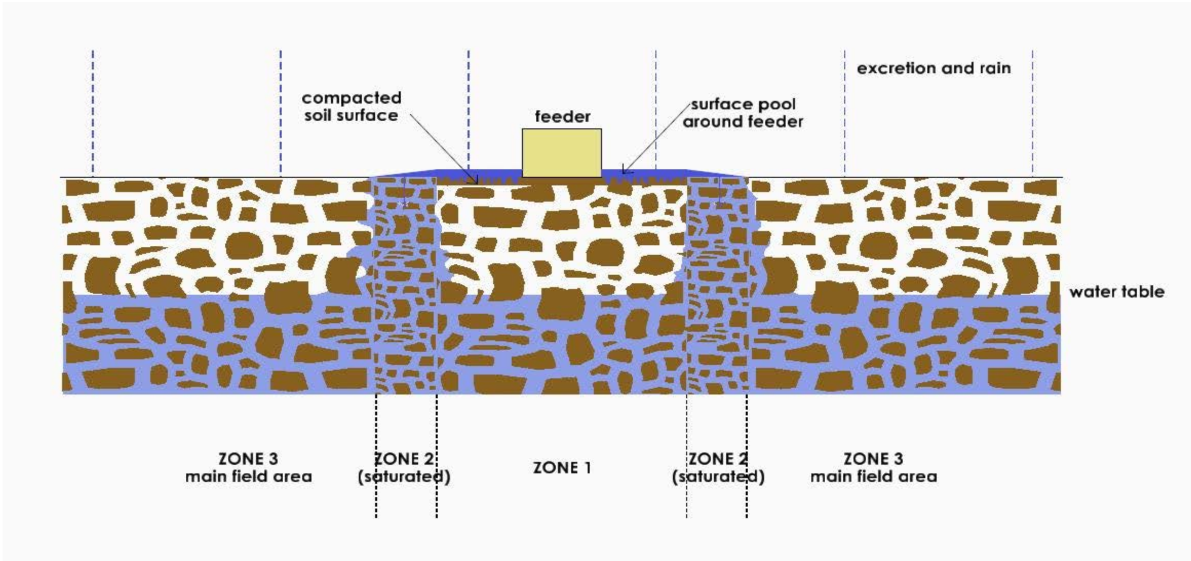

Fig. 1. Cross-section of soil profile showing subdivision of field into zones around feeder

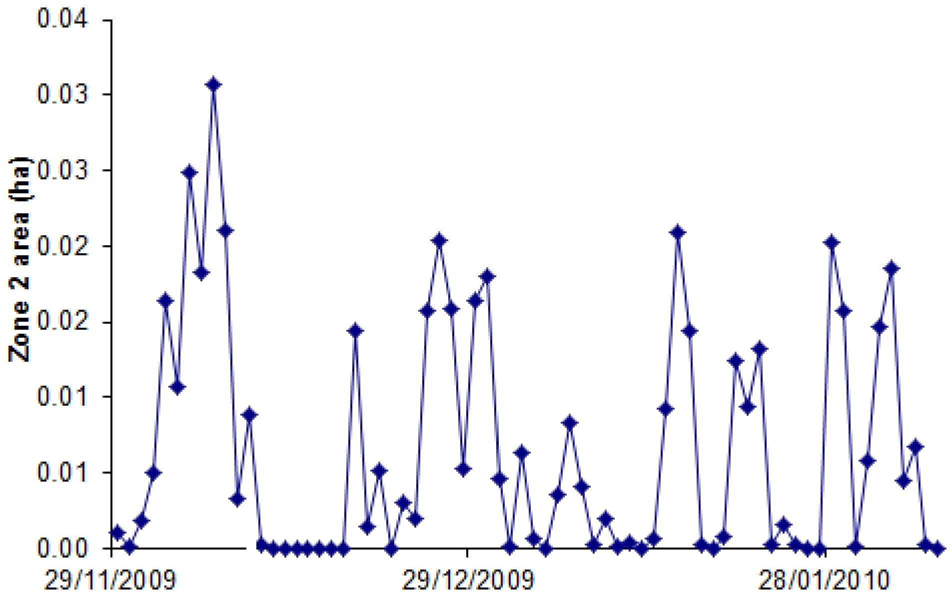

Fig. 2. Area of Zone 2 (Shown for one winter at Welsh site)

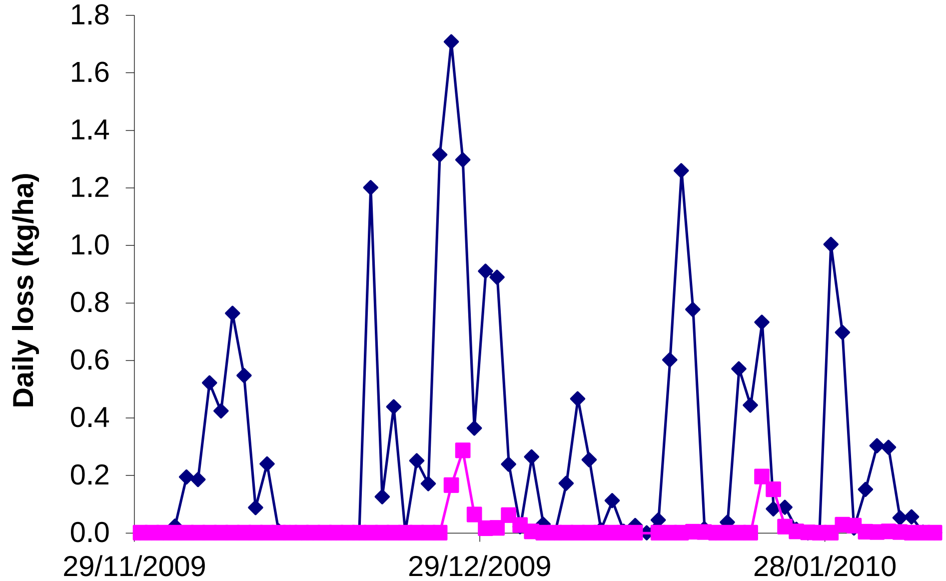

Fig. 3. Daily ammonium loss to drains (shown for one winter at Welsh site)

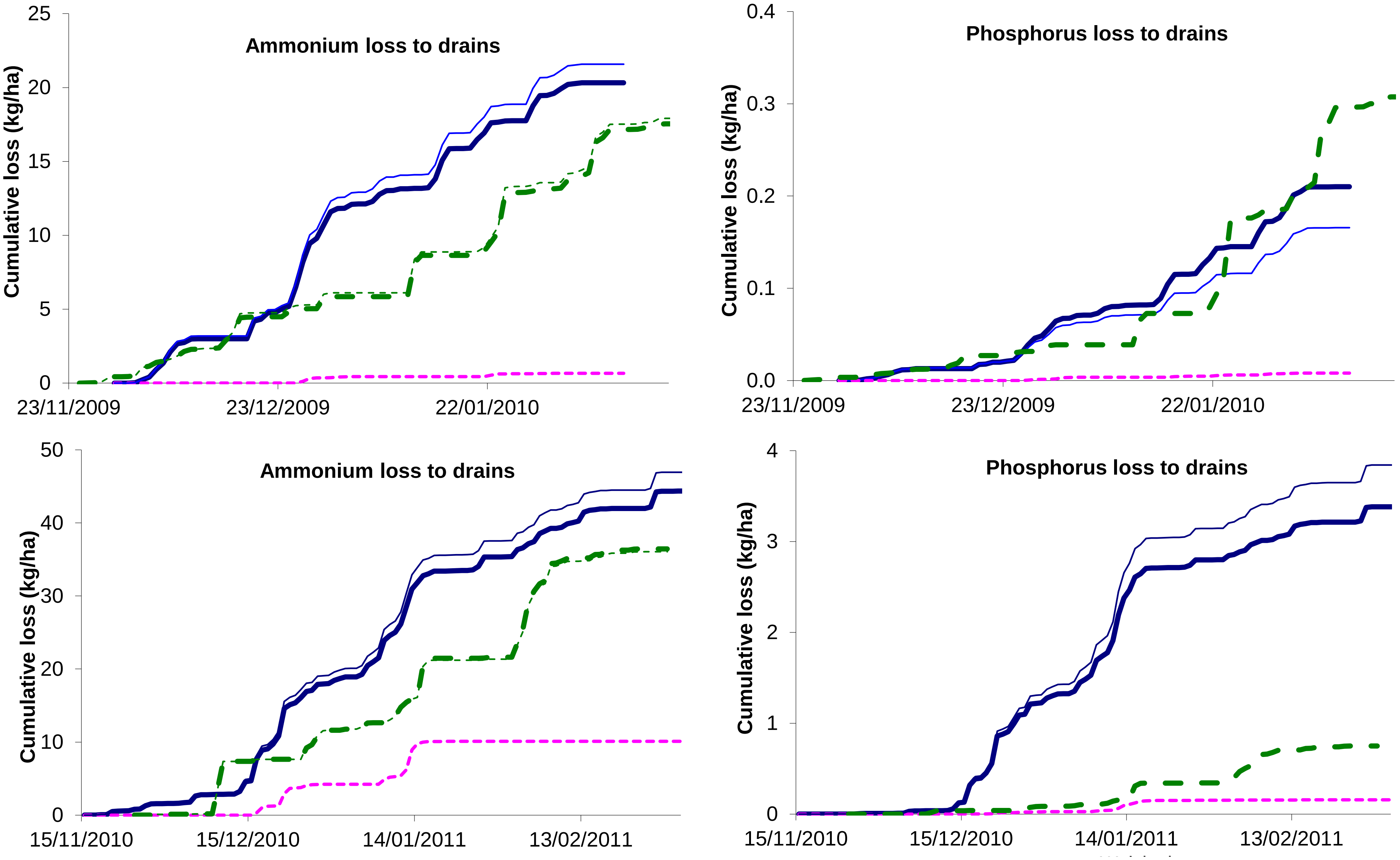

Fig.4. Cumulative losses of contaminants at Welsh and Scottish sites over two winters

Welsh site
Welsh site, without damaged area
Welsh site, scenario with fixed location feeder
Scottish site
Scottish site, scenario with moving feeder